Monitoring Free Flow Traffic using Vehicular Networks

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***Abstract*— We present DTMon, a dynamic traffic monitiroing system using vehicular networks, and analyze its performance in free flow (*i.e.*, non-congested) traffic. DTMon uses roadside infrastructure to gather and report current traffic conditions to traffic management centers and equipped vehicles. We analyze how traffic characteristics such as speed, flow rate, percentage of communicating vehicles, and distance from the DTMon measurement point to the roadside infrastructure affects the amount and quality of data that can be gathered and delivered. We evaluate five different methods of delivering data from vehicles to the roadside infrastructure, including pure vehicle-to-vehicle communication, store-and-carry, and hybrid methods. Methods that employ some amount of store-and-carry can increase the delivery rate, but also increase the message delay. We show that with just a few pieces of roadside infrastructure, DTMon can gather high-quality travel time and speed data even with a low percentage of communicating vehicles.**

I. INTRODUCTION

Real-time monitoring of traffic is an important yet challenging task for traffic management centers. These centers use this data to advise the traveling public about current traffic conditions, including accidents, work zones, and other potential causes of congestion. Traditional methods for collecting traffic data rely on detectors that track vehicles at specific, fixed points. These *point detectors* include inductive loop detectors, video cameras, microwave radar sensors, and acoustic radar sensors [1]. Unfortunately, point detectors cannot be used to directly measure travel times, one of the most desired metrics. Typically, travel times are estimated based on vehicle speed at a single point and the length of the segment in question. This estimation often does not produce high quality data. ILDs, the most commonly-used point detectors, also suffer from the fact that they are expensive to install and maintain.

Newer technologies, such as *probe-based* systems, allow individual vehicles to report statistics as they move through traffic. The most prominent probe-based technologies are automatic vehicle location (AVL) and wireless location tracking (WLT) systems [1, 2, 3]. AVL systems are typically deployed in freight vehicles to assist owners with tracking their shipments and the data produced is proprietary and not widely shared. As freight trucks have different travel characteristics than most other vehicles, the collected data also have their own issues. WLT systems track the presence of mobile phones in vehicles, but they typically rely on coarse-grained positioning (based on cell towers) that cannot reliably identify roadways and they track each phone as a different vehicle even though a single vehicle may contain multiple phones, so the data collected is not yet high quality. Probe-based systems also have an issue due to sampling. Typically, only a small subset of the vehicle population is equipped to gather statistics. The *market penetration rate*, or the percentage of vehicles that are equipped, can greatly affect the quality of data collected.

Vehicular ad-hoc networks (VANETs), consisting of vehicles with GPS and Dedicated Short Range Communication (DSRC) [4] devices, can be used as a powerful probe-based technology. Equipped vehicles are able to compute and record their location and speed at specific times. As a result, vehicles can directly measure their travel time between two specific points. When coupled with road-side units (RSUs), VANETs can be used to measure and report travel times directly to traffic management centers (TMCs).

We extend our previous work [5] on traffic monitoring using vehicular networks and introduce the DTMon system. DTMon consists of *task organizers* (TOs) and *virtual strips* (VS) to collect common traffic data using VANETs. TOs are RSUs that can communicate with equipped vehicles and with a TMC. These TOs can be programmed by the TMC to task vehicles with performing traffic measurements over various sections of the roadway. VS, unlike physical ILDs, are virtual measurement points for TOs and are represented in the form of latitude, longitude, and altitude coordinates. VS can be located anywhere on the roadway, changed dynamically, and used to measure wide areas of the roadway network. For example, a TO could task passing vehicles with reporting their travel time between two particular VS, and as traffic conditions change, the TO could move these VS (or add VS) to measure the travel times over a different region of interest. Once reports have been gathered from vehicles, the TOs can directly communicate information to passing vehicles. This is a vast improvement over current technology, where specific measurement points must be decided on in advance and hardware installed in those locations.

In this paper, we focus on evaluating methods of delivering messages about travel times from vehicles to a TO in the face of low market penetration rates in free-flow (*i.e.*, non-congested) highway traffic. We use the default DSRC/IEEE 802.11p [6] communications range of 300 *m*. Because TOs are physical devices and will be placed at fixed locations on the roadside, we anticipate that most VS will be placed more than 300 *m* from the TO as monitoring needs indicate. Thus, VANET forwarding techniques will need to be employed to deliver messages from vehicles passing a VS to the TO. We focus on message delivery in highway traffic because vehicles are more likely to be disconnected from each other on highways than in urban roadways with intersections. DTMon allows for the use of multiple TOs in a region, providing delivery of messages when VANET forwarding to the original TO is not possible. We show that with the use of multiple TOs, DTMon can provide high quality travel time and speed data even with market penetration rates as low as 5%.

II. Message Reception In Free Flow Traffic

Here, we analyze the impact that various traffic characteristics, including speed, flow rate, and market penetration rate, can have on the amount of information delivered to a TO.

The *message reception rate* (MRR) for a particular VS is the percentage of messages generated by equipped vehicles passing the strip that were received by the TO. The *information reception rate* (IRR) for a particular VS is the percentage of messages received by the TO out of all possible messages generated by vehicles passing the strip (*i.e.*, as if all vehicles were equipped). The IRR indicates how well count information can be collected by the TOs under scenarios with different market *penetration rates* (PR). The upper limit of the IRR is equal to the PR. The IRR is simply the product of the MRR and the PR. Thus, if the PR is 100%, then IRR = MRR.

We consider several traffic characteristics in our analysis, including inter-vehicle spacing, density, flow rate, and mean speed. Inter-vehicle spacing is the distance between vehicles [7, 8]. Density is the number of vehicles occupying a certain area, usually represented in vehicles/*km*. Flow rate is the number of vehicles passing a certain point over a certain amount of time, usually represented in vehicles/*h*. In free-flow traffic, the mean speed typically follows a normal distribution [9]. The relationship between inter-vehicle spacing, flow rate, and mean speed is expressed in Equation 1 and 2:

$$\beta \approx \frac{S}{v} \tag{1}$$

$$\frac{S}{v_{max}} \le \beta \le \frac{S}{v_{min}} \tag{2}$$

where β is the inter-vehicle spacing, S is the mean speed of vehicles, and v is the flow rate ($v_{min} \le v \le v_{max}$). Density is $1/\beta$.

The flow rate in low and medium density traffic can have three different types of distributions: Poisson, exponential, or uniform [9]. According to the derived equations for inter-vehicle spacing with an exponential distribution [7, 8], the probability that messages are forwarded successfully is very low for distances farther than the transmission range of the TO, taking into account the market penetration rate.

The flow rate in very low density traffic has a Poisson distribution. The probability that the spacing of equipped vehicles in an interval is less than the communication range is zero, taking into account the PR and traffic speed. Therefore, the chance that a message is able to be forwarded even a short distance will be zero. The conclusion is that in very low density traffic, the IRR will be very small and TOs will not receive any messages from outside their communication range. Therefore, methods other than message forwarding must be considered to improve the IRR in such traffic conditions.

For the remainder of this section, we consider medium to high density traffic, where the flow rate v varies in a limited range and the inter-vehicle spacing β will have a uniform distribution. Adding in the market penetration rate p, we can calculate the inter-vehicle spacing of equipped vehicles E_p as shown in Equation 3:

$$E_p \approx \frac{\beta}{p} = \frac{S}{pv} \tag{3}$$

$$\lambda_{min} \le E_p \le \lambda_{max} \tag{4}$$

$$\lambda_{min} = \frac{S}{pv_{max}} \; and \; \lambda_{max} = \frac{S}{pv_{min}} \tag{5}$$

where $1 < p < 0$. Note that $E_{1.0} = \beta$ and $E_{0.0} = \infty$.

E_p, the inter-vehicle spacing of equipped vehicles with market penetration rate p, has an uniform distribution according to Equation 3, 4 and 5. Equations 6 and 7 show the probability density function (pdf) and cumulative distribution function (cdf) of E_p, respectively.

$$f_{E_p}(x) = \frac{1}{\lambda_{max} - \lambda_{min}} \tag{6}$$

where $\lambda_{min} \le x \le \lambda_{max}$ otherwise $f_{Ep}(x) = 0$.

$$F_{E_p}(x) = \frac{x - \lambda_{min}}{\lambda_{max} - \lambda_{min}}, \lambda_{min} \le x \le \lambda_{max} \tag{7}$$

$$F_{E_p}(x) = 0, x \le \lambda_{min}$$

$$F_{E_p}(x) = 1, x \ge \lambda_{max}$$

Equation 8 shows the expected value of the inter-vehicle spacing E_p.

$$E[E_p] = \frac{\lambda_{max} + \lambda_{min}}{2} \tag{8}$$

In this analysis, we assume that a connection between two equipped vehicles can only take place if the spacing between them does not exceed the maximum DSRC transmission range R_0 and propagation loss is negligible. For a vehicle to forward a message, it must be able to find at least one equipped vehicle in its neighbor list within R_0. Equation 9 shows the probability of a connection between two vehicles, $P_{connected}$.

$$P_{connected} = P\{E_p \le R_0\} = F_{E_p}(R_0) \tag{9}$$

The probability that two vehicles are disconnected, meaning that the message cannot be forwarded farther is 1- $P_{connected}$.

A message can be forwarded through a group of connected vehicles (*i.e.*, a cluster of equipped vehicles). The inter-vehicle spacing C in a cluster of connected vehicles will have the following pdf:

$$f_C(x) = P\{E_p | E_p < R_0\} = \frac{x - \lambda_{min}}{R_0 - \lambda_{min}} \tag{10}$$

Therefore, the average distance between two connected vehicles in a cluster will be:

$$E[C] = \frac{R_0 + \lambda_{min}}{2} \tag{11}$$

In a segment of size d (*e.g.*, the distance between a VS and a TO), the probability of having a successful message reception by a TO can be estimated by knowing the average number of hops required and the probability of connectivity at each hop as shown in Equation 12:

$$f_{reception}(d) \approx (P_{connected})^{n-1}, n = \left\lfloor \frac{d}{E[C]} \right\rfloor \tag{12}$$

Equation 12 implies that it takes on average n-1 hops (last hop directly talks to the TO) to forward a message to the TO. The probability of connectivity at each hop is determined by Equation 9 which implicitly considers the traffic density (also traffic in the opposite direction, if any), traffic speed, market penetration rate, and DSRC communication range R_0.

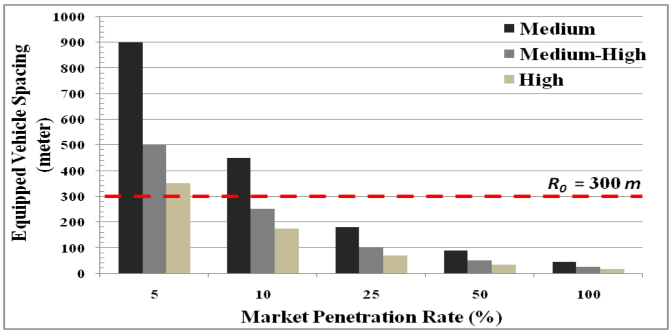

Figure 1. Expected inter-vehicle spacing for different market penetration rates with medium (1800 veh/h) and higher flow rates (3600 and 5400 veh/h).

Theoretically, the maximum equipped inter-vehicle spacing λ_{max} will be less than R_0 (300 *m*) and $P_{connected}$ will be 1.0 (100%) when the penetration rate p is above 0.1 (10%) for flow rates $v_{min} \leq v \leq v_{max}$. Figure 1 shows that the expected inter-vehicle spacing is above R_0 for p less than or equal to 10% even with a high traffic flow rate. Therefore, the probability that a message is successfully forwarded a distance of 1000 *m* or longer is zero. These results emphasize the fact that using TOs and message forwarding may only work in a highly equipped system. The farther the distance between the VS and the TO, the higher the traffic density must be and the more vehicles that must be equipped to achieve a high IRR. Therefore, with low PR, either VS should be placed near TOs or methods that avoid forwarding should be used to produce a high MRR. Our analysis does not consider fading effects, which would only make the conclusions stronger. In many situations, it is not feasible to use a forwarding-only message delivery scheme and other methods should be examined.

III. Message Delivery Methods

In DTMon, TOs broadcast tasks periodically. The tasks contain information about the TO's location, the locations of VS, and the locations of other nearby TOs. Equipped vehicles in the transmission range of the TO receive and store tasks that will be triggered upon passing the indicated VS. When a task is triggered, a vehicle will generate a message that includes its speed, location, time, and any metrics that were requested. The vehicle will try to forward this message using vehicle-to-vehicle communications to the nearest TO. We assume that TOs are connected to a central server, possibly at the TMC. If the nearest TO was not the original TO that issued the task, the information can still be aggregated with reports delivered to the original TO through the central server.

We investigate the following methods of message delivery to improve the MRR, and therefore the IRR:

- *Regular Forwarding (RF)* – A vehicle passing a VS will forward the message to the closest possible TO from the list of TOs defined in the task.
- *Dynamic Transmission Range (DTR)* **–** A vehicle will use RF initially with the standard DSRC range of 300 *m*. If the message cannot be forwarded (*i.e.*, there is no vehicle within 300 *m*), then the vehicle will increase its transmission range to 600 *m*. If the vehicle is still not able to find a neighbor, it will increase its transmission range to 1000 *m*. Note that IEEE 802.11p [6] allows for transmission power settings that can result in a range of 1000 *m* in certain instances.
- *Store-and-Carry (SAC)* **–** A vehicle will store the message and carry it to the next TO.
- *RF+SAC* – A vehicle will forward the message to the closest TO using RF and will also store and carry the message to the next TO in order to ensure reception by a TO. Duplicate reports are detected by the central server using the message generation time and location.
- *DTR+SAC* - A vehicle will forward the message to the closet TO using DTR and also store and carry the same message to the next TO.

In bi-directional roadways, vehicles traveling in the opposite direction can participate in forwarding or carrying messages, which may further improve these methods.

IV. Evaluation

We performed several experiments using VANET modules that we developed [10] for the *ns-3* simulator [11]. The goal was to compare the message reception rates and message delays of the delivery methods described in Section III under various market penetration rates. Using SAC will increase the reception rate (Section IV.A), but comes with the tradeoff of increasing the message delay (Section IV.B). We note that a 100% reception rate does not mean that all of the possible information is collected as only equipped vehicles can report to the TO. We consider the question of traffic data quality and the information reception rate in Section IV.C.

We focus on the highway scenario to highlight situations with potentially poor connectivity. We used a six-lane bi-directional highway with two TOs and four VS as shown in Figure 2. The subscripts on the TO and VS labels indicate their distance in *km* from the highway entrance. Vehicles enter the highway with a medium flow rate (average of 1800 *veh/h*) and a desired speed between 30±5 *m/s* (110±18 *km/h*). We performed 10 30-minute simulation runs for each message delivery method and averaged the results.

In each experiment, TO_1 tasked passing vehicles with reporting when they passed VS_2, VS_5, and VS_9. Depending on the message delivery method, these reports were delivered back to TO_1 or were delivered to TO_5.

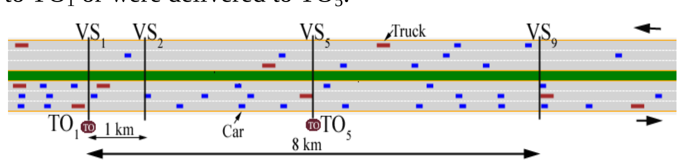

Figure 2. A six-lane bi-directional highway with two TOs and four VS.

A. Message Reception Rate

The results shown in Figure 1 indicate that with a medium flow rate and a 300 *m* communication range, market penetration rates (PR) of 10% and below will result total disconnectivity as the average equipped inter-vehicle spacing is higher than the communication range. Thus, with a PR of 5-10%, no messages will be received by TO_1 from VS_2 or farther strips when regular forwarding (RF) is used. With a PR of 5%, the situation is the same for dynamic transmission range (DTR). Our simulations use the Log-distance signal fading model, so even though Figure 1 indicates that the average inter-vehicle spacing is less than the maximum range of 1000 *m*, the signal is not actually able to propagate that far. Since there is total disconnectivity, the SAC methods, including RF+SAC and DTR+SAC, will have equal performance, as all messages will be carried to TO_5. This will increase the message reception rate (MRR) from 0% to 100% and the information reception rate (IRR) will be equal to the PR.

Figure 3 shows $F_{reception}$ calculated by Equation 12 and the probability of reception by TO_1 obtained by simulation using RF with PRs of 50% and 100%. The simulation produced an average speed of 27.45 *m/s*, so that was the speed used for *S* in Equation 12. The simulation results match the equation well. The MRR drops when the VSs are farther from TO_1. Even with 100% PR, TO_1 will miss 10% of the messages from VS_2 (1 *km* away) and about 30% of messages from VS_5 (4 *km* away).

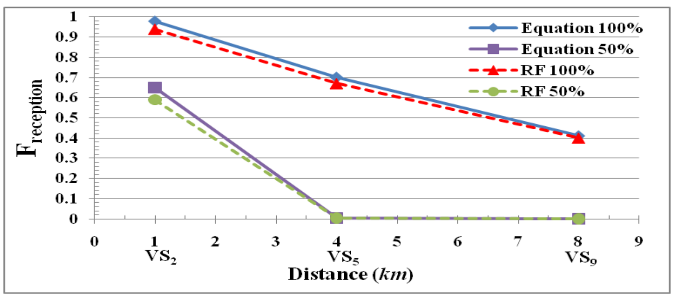

Figure 3. $F_{reception}$ based on the distance from the VS to TO_1.

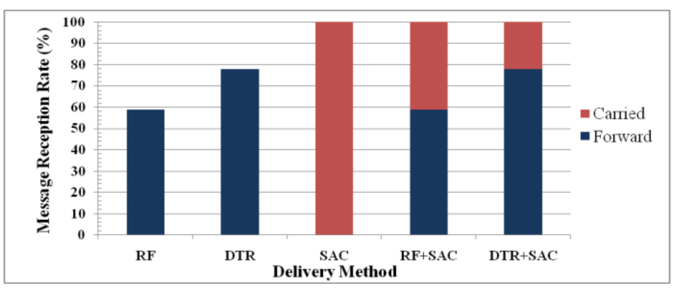

Figure 4. MRR from VS_2 with 50% PR.

Figure 4 shows the MRR for messages from VS_2 using different delivery methods with 50% PR. The figure also indicates what portion of the MRR is due to forwarding to TO_1 or carrying to TO_5. RF results in over 50% MRR, and DTR improves that to over 75%. But, the addition of SAC (either alone or in combination with RF or DTR) results in 100% MRR. Any messages that cannot be forwarded back to TO_1 are able to be carried and delivered successfully to TO_5.

Figure 5 shows how the MRR is affected by the distance of the report origination from TO_1 with 50% PR. Note that because of carrying, the distance does not affect the delivery results when SAC is used. For both RF and DTR, the MRR drops dramatically when the distance from TO_1 is increased. This is due to periods of disconnectivity in the traffic when the message cannot be forwarded back to TO_1. Thus, if the VS is far from the originating TO, SAC methods should be used to achieve high MRR.

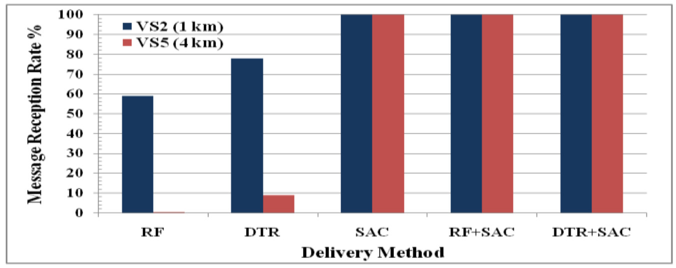

Figure 5. MRR from VS_2 (1 *km* away) and VS_5 (4 *km* away) with 50% PR.

Using vehicles traveling in the opposite direction on bi-directional roadways can decrease the equipped inter-spacing for message delivery and therefore improve the MRR. Table I shows the MRR when traffic in the opposite direction (with the same medium flow rate) is also used for forwarding. With a 50% PR, using opposite direction traffic with either RF or DTR improves the MRR from VS_2 by 20-25%. For DTR, this results in a total MRR of close to 100%. Unfortunately, since the opposite direction traffic has the same flow rate as the forward direction, there is still much disconnectivity with a 5% PR and thus, little or no improvement in the MRR.

TABLE I. MRR FROM VS_2 USING TRAFFIC IN OPPOSITE DIRECTION

Penetration Rate	RF, w/o opp	RF, w/opp	DTR w/o opp	DTR, w/opp
5%	0%	0%	1.1%	2.4%
50%	59%	72%	78%	96.7%

B. Message Delay

Message delay is the time from a message being generated by a vehicle until the message is received at a TO (either TO_1 or TO_5). Figures 4 and 5 showed that SAC greatly improves the MRR, but there is a tradeoff in increased delay, which may impact its usefulness in obtaining real-time traffic statistics.

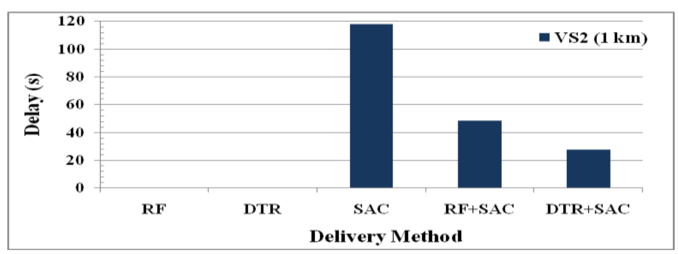

Figure 6. Average message delay from VS_2 with different delivery methods.

Figure 6 shows the average message delay from VS_2 to a TO (either TO_1 or TO_5) for the different delivery methods. When delivery is successful, RF and DTR have very low delay, on the order of milliseconds. SAC has the highest delay because of the travel time that vehicles encounter while driving towards TO_5. Using SAC combined with message forwarding will reduce this delay. For example, where the average delay for SAC alone is 118 *s*, the average delay for RF+SAC is about 50 *s*. This is because 59% of the messages with RF+SAC are able to be forwarded to TO_1 using RF, which has a delay of only 7 *ms*. The remaining 41% were carried to TO_5 with an average delay of 118 *s*, which is the average travel time for a 3 *km* segment. The distance between the TOs and the distance from the VS to the closest TO has a direct impact on message delay using SAC. Using traffic in the opposite direction may reduce the overall message delay by allowing more forwarding to take place. In Figure 6 we only show messages originating at VS_2 because VS_5 is co-located with TO_5 and thus, would have no delay regardless of the forwarding method. Even if there were only one TO (*e.g.*, TO_1), a successful delivery using RF or DTR would have a delay on the order of milliseconds.

C. Quality of Traffic Data

TMCs are interested in gathering travel times and traffic speeds over certain sections of the highway. There are two types of speed that TMCs consider, *time mean speed* (TMS) and *space mean speed* (SMS). TMS is the average speed of vehicles passing a *point* on a roadway, and SMS is the average speed of vehicles based on the average travel time of vehicles traversing a *segment* of roadway. DTMon can only count equipped vehicles therefore, traffic flow rate and density estimates are precise only with a high PR. But, DTMon can provide high quality estimates of travel time and traffic speed with just a few received messages, thus it can be used even in low PR situations.

TABLE II. T-TEST 5% PR (ALPHA = 0.05)

	Actual		RF+SAC		t-Stat	p-Value	Sig.?
	Mean	*Var*	*Mean*	*Var*			
TMS	27.26	0.13	26.65	1.21	-9.7002	0.0006	Yes
TT	39.88	0.19	39.38	12.97	0.3165	0.7673	No
SMS	25.07	0.40	25.39	2.0	-0.3117	0.8076	No

Table II shows the results of a t-test (alpha=0.05) between actual traffic data and the traffic data collected by the TOs (using RF+SAC) from VS_2 with 5% PR. The estimates we consider here are time mean speed (TMS) in *m/s*, travel time (TT) in *s*, and space mean speed (SMS) in *m/s*. The results show that DTMon can be used to estimate TT and SMS with 95% confidence for PRs as low as 5%. Note that with the 100% MRR provided by RF+SAC and 5% PR, the information reception rate (IRR) is only 5%. So, these results show that TT and SMS can be accurately estimated with as little as 5% of the traffic reporting. It does not matter whether this is due to low PR or low MRR. We note that there is a significant difference between the actual TMS and the estimated TMS at 5% PR. This is because there are so few samples (*i.e.*, equipped vehicles) at the particular point used for computing the TMS. With an increase in the PR to 50%, the TMS is more accurate. Table III shows the results of a t-test between RF+SAC and actual data with 50% PR. Here, there is no significant difference between the actual data and that collected by the TOs.

TABLE III. T-TEST 50% PR (ALPHA =0.05)

	Actual		RF+SAC		t-Stat	p-Value	Sig.?
	Mean	*Var*	*Mean*	*Var*			
TMS	26.34	0.23	27.08	0.67	1.0689	0.2005	No
TT	40.62	0.28	38.84	0.05	0.4025	0.5127	No
SMS	24.62	0.03	25.74	0.01	2.2064	0.3911	No

Since the forwarding method can affect the number of samples received by the TOs, we look at how well the data obtained using RF compared to RF+SAC with 50% PR. We show the results of the t-test in Table IV. There is no significant difference between the data collected with RF+SAC and with RF. So with a higher PR, TMCs could use forwarding-only techniques to lower the message delay, while still receiving high quality estimates.

TABLE IV. T-TEST 50% PR (ALPHA =0.05).

	RF		RF+SAC		t-Stat	p-Value	Sig.?
	Mean	*Var*	*Mean*	*Var*			
TMS	27.45	0.41	27.08	0.67	2.9473	0.2082	No
TT	39.17	1.35	38.84	0.05	0.5075	0.7010	No
SMS	25.52	2.01	25.74	0.01	0.0521	0.9668	No

V. CONCLUSIONS AND FUTURE WORK

In this paper, we analyzed the ability of DTMon to provide high-quality traffic data in free-flow traffic with low to medium market penetration rates. We introduced the information reception rate (IRR) and showed how it was affected by the market penetration rate, traffic speed, traffic flow rate, and distance of the measurement point (VS) from the TO. The IRR directly impacts the quality of certain traffic data. We evaluated different methods of delivering messages to improve the IRR and showed that an improvement in the message reception rate can have the cost of increased message delay. But, regardless of the method of message delivery, we showed that DTMon can collect high-quality travel time and speed data in free-flow traffic where the possibility of receiving messages from just a few vehicles exists.

In future work, we plan to investigate the ability of DTMon to deliver high-quality data in transient congested traffic. For this type of traffic, we are particularly interested in detecting congestion and monitoring end-of-queue situations.

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